State of California
The Resources Agency
Department of Water Resources
Bay-Delta Office

Methodology for Flow and Salinity Estimates in the Sacramento-San Joaquin Delta and Suisun Marsh

Twenty-ninth Annual Progress Report to the
State Water Resources Control Board in
Accordance with Water Right Decisions 1485 and 1641

June 2008

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Governor
State of California

Mike Chrisman
Secretary for Resources
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Lester A. Snow
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Foreword

This is the 29th annual progress report of the California Department of Water Resources' San Francisco Bay-Delta Evaluation Program, which is carried out by the Delta Modeling Section. This report is submitted annually by the section to the California State Water Resources Control Board pursuant to its Water Right Decision 1485, Term 9, which is still active pursuant to its Water Right Decision 1641, Term 8.

This report documents progress in the development and enhancement of the Bay-Delta Office's Delta Modeling Section's computer models and reports the latest findings of studies conducted as part of the program. This report was compiled under the direction of Tara Smith, program manager for the Bay-Delta Evaluation Program.

Online versions of previous annual progress reports are available at:
http://baydeltaoffice.water.ca.gov/modeling/deltamodeling/annualreports.cfm

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Acronyms and Abbreviations

ANNs	Artificial Neural Networks
cfs	cubic feet per second
CVP	Central Valley Project (federal)
DRMS	Delta Risk Management Strategy
DSM2	Delta Simulation Model 2
EC	electrical conductivity
IPCC	Intergovernmental Panel on Climate Control
KM	Kimmerer-Monishmith
MHHW	mean higher high water
MHW	mean high water
MLLW	mean lower low water
MLW	mean low water
MSL	mean sea level
QUAL	water quality parameter
SRES	Special Report on Emission Scenarios
SWP	State Water Project
taf	thousand acre-feet
WY	water year

Metric Conversion Table

Quantity	*To Convert from Metric Unit*	*To Customary Unit*	*Multiply Metric Unit By*	*To Convert to Metric Unit Multiply Customary Unit By*
Length	millimeters (mm)	inches (in)	0.03937	25.4
	centimeters (cm) for snow depth	inches (in)	0.3937	2.54
	meters (m)	feet (ft)	3.2808	0.3048
	kilometers (km)	miles (mi)	0.62139	1.6093
Area	square millimeters (mm^2)	square inches (in^2)	0.00155	645.16
	square meters (m^2)	square feet (ft^2)	10.764	0.092903
	hectares (ha)	acres (ac)	2.4710	0.40469
	square kilometers (km^2)	square miles (mi^2)	0.3861	2.590
Volume	liters (L)	gallons (gal)	0.26417	3.7854
	megaliters (ML)	million gallons (10*)	0.26417	3.7854
	cubic meters (m^3)	cubic feet (ft^3)	35.315	0.028317
	cubic meters (m^3)	cubic yards (yd^3)	1.308	0.76455
	cubic dekameters (dam^3)	acre-feet (ac-ft)	0.8107	1.2335
Flow	cubic meters per second (m^3/s)	cubic feet per second (ft^3/s)	35.315	0.028317
	liters per minute (L/mn)	gallons per minute (gal/mn)	0.26417	3.7854
	liters per day (L/day)	gallons per day (gal/day)	0.26417	3.7854
	megaliters per day (ML/day)	million gallons per day (mgd)	0.26417	3.7854
	cubic dekameters per day (dam^3/day)	acre-feet per day (ac-ft/day)	0.8107	1.2335
Mass	kilograms (kg)	pounds (lbs)	2.2046	0.45359
	megagrams (Mg)	tons (short, 2,000 lb.)	1.1023	0.90718
Velocity	meters per second (m/s)	feet per second (ft/s)	3.2808	0.3048
Power	kilowatts (kW)	horsepower (hp)	1.3405	0.746
Pressure	kilopascals (kPa)	pounds per square inch (psi)	0.14505	6.8948
	kilopascals (kPa)	feet head of water	0.32456	2.989
Specific capacity	liters per minute per meter drawdown	gallons per minute per foot drawdown	0.08052	12.419
Concentration	milligrams per liter (mg/L)	parts per million (ppm)	1.0	1.0
Electrical conductivity	microsiemens per centimeter (µS/cm)	micromhos per centimeter (µmhos/cm)	1.0	1.0
Temperature	degrees Celsius (°C)	degrees Fahrenheit (°F)	(1.8X°C)+32	0.56(°F-32)

1 Introduction

The California Department of Water Resources uses the Delta Simulation Model II (DSM2) to simulate conditions on the Sacramento-San Joaquin Delta. The DSM2-Qual model simulates water quality—multiple conservative and non-conservative constituents—in a 15 minute time-step. CalSim II, an application of the generic CalSim model, simulates State Water Project and Central Valley Project operations.

The following are brief summaries of modeling work conducted during the past year. The names of contributing authors are in parentheses.

Chapter 2 – Magnitude of Dispersion Factor Used in DSM2-Qual

When modeling with DSM2-Qual, the key parameter affecting mixing is the dispersion factor, a calibrated parameter applied independently to each channel reach. The Qual dispersion factor differs from the classical dispersion coefficient. This chapter discusses how the DSM2 and classical dispersion formulas relate to one another and how to determine reasonable ranges for the DSM2 coefficient based on estimates in the literature. (*Qiang Shu*)

Chapter 3 – Impacts of Sea Level Rise and Amplitude Change on Delta Operations

This chapter quantifies impacts on Delta operations and salinity increases at some key locations of the Delta due to sea level rise and change in tidal amplitude. With DSM2, we calculated the salinity at key locations in the Delta and trained Artificial Neural Networks (ANNs) for the sea-level-rise scenarios. With CalSim II (Central Valley Project and State Water Project operation model), we determined the extra cost of water to mitigate the sea level rise and tidal amplitude change. We assumed that current operation rules (D1641) were unchanged for this study. (*Sanjaya Seneviratne, Shengjun Wu, and Yiguo Liang*)

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Chapter 2:
Magnitude of Dispersion Factor Used in DSM2-Qual

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2 Magnitude of Dispersion Factor Used in DSM2-Qual

2.1 Introduction

When modeling with Delta Simulation Model II (DSM2)-Qual, the key parameter affecting mixing is the dispersion factor, a calibrated parameter applied independently to each channel. The dispersion factor differs from the classical dispersion coefficient described in Fischer *et al.* (1979). This chapter discusses how the DSM2 and classical dispersion formulas relate to one another and how to determine reasonable ranges for the DSM2 coefficient based on estimates in the literature.

2.2 Methodology and Application

2.2.1 Classic Transportation Equation and Dispersion Coefficient

With reference to the lagrangian longitudinal-axis ξ (axis moving in the cross-section average flow velocity) and without considering tributary flow, reaction, and production, the one-dimensional transport equation is expressed as

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial \xi}(D\frac{\partial C}{\partial \xi}) \qquad (2.1)$$

in which C is the cross-sectional average concentration, *t* is time, ξ is distance along the reference axis, and D is the dispersion coefficient [L^2 / T]. Dispersion coefficient D is a macro indicator of the diffusing ability of the flow under study.

2.2.2 Approximation of Classic Transportation Used by DSM2-Qual

In DSM2-Qual, equation 2.1 is evaluated by taking the integral on both sides for a water parcel as

$$\int_{t}^{t+\Delta t} \frac{\partial C}{\partial t} dt = \int_{t}^{t+\Delta t} \frac{\partial}{\partial \xi}(D\frac{\partial C}{\partial \xi})dt \qquad (2.2)$$

in which Δt is the time step. The left side of equation 2.2 is just $C_{t+\Delta t} - C_t$; the right side of equation 2.2 is evaluated approximately by a single, explicit finite difference formula (Jobson and Schoellhamer 1993)

Equation 2.3 is the discretized, approximate form of equation 2.2. The derivation of equation 2.3 is presented in Appendix 2A.

$$\int_{t}^{t+\Delta t} \frac{\partial}{\partial \xi}\left(D\frac{\partial C}{\partial \xi}\right)dt \approx \frac{|Q|\Delta t}{V_p}\left[D_f^{+}(C^{+}-C)-D_f^{-}(C-C^{-})\right] \tag{2.3}$$

in which $|Q|$ is the channel discharge, V_p is the water parcel volume, D_f^{+} and D_f^{-} are dimensionless dispersion factors at the upstream and downstream ends of the water parcel, and C^{+} and C^{-} are the concentrations in the parcel that are on upstream and downstream sides, respectively. All terms on the right side of equation 2.3 are evaluated at the previous time step t-Δt.

This approximation introduces a dimensionless dispersion factor D_f, which is defined as

$$D_f = \frac{D}{|u|\Delta x} \tag{2.4}$$

in which $|u|$ is the absolute value of mean cross-section velocity, and Δx is the parcel length. This definition shows the dispersion factor D_f used in Qual is a ratio of dispersion to advection, and D_f is dimensionless. It is obvious that the value of D_f can be estimated roughly based on the value of D.

2.2.3 Estimating Dispersion Coefficient

It is important to do a reasonable estimate of dispersion factor D_f, which controls speed of mass transport. In the following sections, guidelines are presented to do such an estimate based on an empirical formula and field experiment results of estuary presented by Fischer *et al.* (1979).

2.2.4 Using Empirical Formula of Real Stream

In real streams, especially wide streams, the dispersion caused by the transverse velocity profile becomes a significant part of the longitudinal dispersion process, which makes dispersion a 2-dimensional problem. Sometimes, the transverse profile causes dispersion that is 100 times greater than the vertical profile (Fischer *et al.* 1979).

To account for the behavior described above, Fischer *et al.* (1979) gave a formula:

$$D = \frac{0.011uW^2}{du^*} \tag{2.5}$$

in which u is the mean cross-sectional velocity, W is river width, d is flow depth, and u^* is shear velocity defined as:

$$u^* = \sqrt{gds} \tag{2.6}$$

in which g is the acceleration due to gravity ($32.2 ft^2/s$), and s is the channel bottom slope.

Based on previous analysis, the dimensionless dispersion factor D_f used in Qual can be evaluated by using equation 2.5 in equation 2.4.

From equation 2.7, it is clear the value of dispersion factor depends on channel geometry and discharge—the bigger the discharge, the bigger the dispersion factor. Although DSM2-Qual does not allow for a varied dispersion factor at this time, we can do a rough estimate of the possible range of factor values.

$$D_f = \frac{0.011|u|W^2}{du^*\Delta x} \tag{2.7}$$

Equation 2.7 provides valuable help in evaluating the dispersion factor for wide channels used in DSM2-Qual modeling work. It is more physically meaningful to lump dispersion effects caused by transverse flow velocity into the magnitude of the dispersion factor because DSM2 hydrodynamics cannot simulate such velocity profile.

For instance, channel 640, a wide channel used in the DSM2 extension grid, has the following physical parameters:

- simulated high discharge, 700,000 *cfs*
- parcel length, $\Delta x = 2000\,ft$
- channel width, $W = 8000\,ft$
- typical depth, $d = 50\,ft$
- slope estimated as $S = 0.0008$

Then shear velocity is $u^* = \sqrt{32.2 * 50 * 0.0008} = 1.135\,ft/s$. Mean flow velocity is

$|u| = \frac{700000}{8000 * 50} = 1.75\,ft/s.$ So we can estimate a possible high value of the dispersion factor as

$$D_f = \frac{0.011 * 1.75 * 8000^2}{50 * 1.135 * 2000} = 10.85.$$

Another calculation is done on the channel 133 on Middle River from the standard DSM2 grid as follows

- simulated high discharge, 1028 *cfs*
- parcel length, $\Delta x = 300\,ft$
- channel width, $W = 240\,ft$
- typical depth, $d = 8.7\,ft$
- slope estimated as, $S = 0.000204$

Then shear velocity is $u^* = \sqrt{32.2 * 8.7 * 0.000204} = 0.24\,ft/s$. Mean flow velocity is

$|u| = \frac{1028}{240 * 8.7} = 0.49\,ft/s.$ So we can estimate a possible high value of dispersion factor as

$$D_f = \frac{0.011 * 0.49 * 240^2}{8.7 * 0.24 * 300} = 0.5$$

2.2.5 Using Field Experiment Results of Estuary

An estuary usually has a dispersion coefficient lower than a wide channel of similar size. There are a number of field experiment results in Fischer *et al.* (1979) that can be used to guide modelers to select a reasonable dispersion factor for their DSM2 grid based on equation 2.4:

$$D_f = \frac{D}{|u|\Delta x} \tag{2.4}$$

For instance, field experiments generated a range of 1,000 < D (ft^2/s) < 12,000 at the San Francisco Bay. Based on those results, the estimate of the dispersion factor in channel 640 done in section 2.2.4 is redone using equation 2.4,

$$0.3 < D_f < 3.4$$

2.3 Conclusion

The analysis and example in the previous section suggests the value of dispersion factor for wide channels may increase by orders of magnitude. In the *Users Manual for a Branched Lagrangian Transport Model*, Jobson and Schoellhamer (1993) interpret this dispersion factor as a ratio of inter-parcel mixing flow rate to channel discharge. If this factor is set to a value larger than 1, it may mean dispersion caused by the flow profile is accounted in a direction other than longitudinal. As long as the flow volume caused by the mixing is less than the lesser of 2 neighboring water parcels, using a dispersion factor larger than 1 will not contradict flow and mass continuity condition (Appendix 2A and 2B). A short discussion about Qual performance under high flow is also presented in Appendix 2C.

2.4 References

Fischer, H.B., E.J. List, R.C.Y. Koh, J. Imberger, N.H. Brooks. 1979. *Mixing In Inland and Coastal Waters*. San Diego, CA: Academic Press.

Jobson, H.E. and D.H. Schoellhamer. 1993. *Users Manual for a Branched Lagrangian Transport Model*. Reston, VA: U.S. Geological Survey. Water-Resources Investigation Report 87-4163.

Appendix 2A Derivation of Dispersion Equation

This appendix demonstrates the process of derivation of equation 2.3

$$\int_t^{t+\Delta t} \frac{\partial}{\partial \xi}(D\frac{\partial C}{\partial \xi})dt \approx \frac{|Q|\Delta t}{V_p}[D_f^+(C^+ - C) - D_f^-(C - C^-)]$$

This derivation begins by assuming steady flow, and then extending its usage to transient flows after considering the difference of dispersion coefficient at different water parcels.

Example: Three neighboring cubic water parcels have the same volume, length, and cross-sectional area. Their concentrations of constitutes are C^+, C, and C^- from upstream to downstream, respectively (Figure 2A-1).

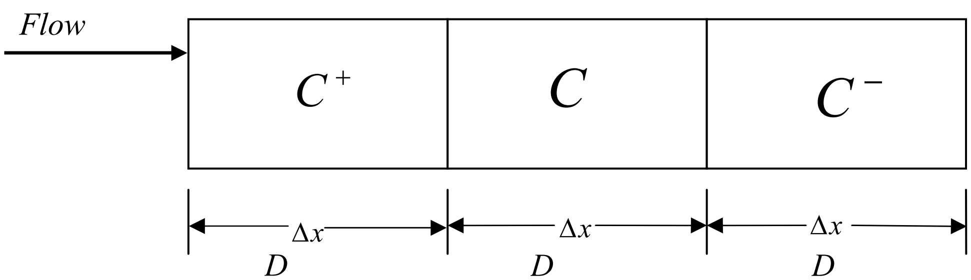

Figure 2A-1 Three neighboring cubic water parcels

Evaluating $\int_t^{t+\Delta t} \frac{\partial}{\partial \xi}(D\frac{\partial C}{\partial \xi})dt$ for the middle water parcel can be done approximately by one step explicit Euler method as equation A.1:

$$\int_t^{t+\Delta t} \frac{\partial}{\partial \xi}(D\frac{\partial C}{\partial \xi})dt \approx (\frac{\partial}{\partial \xi}(D\frac{\partial C}{\partial \xi}))\Delta t \qquad \text{(A.1)}$$

Then derivatives on the right side of equation A.1 can be approximated by the value of $D\frac{\partial C}{\partial \xi}$ at upstream and downstream borders of the water parcel under consideration as

$$\frac{\partial}{\partial \xi}(D\frac{\partial C}{\partial \xi}) \approx (\left(D\frac{\partial C}{\partial \xi}\right)^+ - \left(D\frac{\partial C}{\partial \xi}\right)^-)/\Delta x \qquad \text{(A.2)}$$

where $\left(D\frac{\partial C}{\partial \xi}\right)^{+}, \left(D\frac{\partial C}{\partial \xi}\right)^{-}$ are values of $D\frac{\partial C}{\partial \xi}$ at the upstream and downstream borders respectively.

Then $\left(D\frac{\partial C}{\partial \xi}\right)^{+}, \left(D\frac{\partial C}{\partial \xi}\right)^{-}$ can be approximated based on the dispersion coefficient and concentration at neighboring parcels as

$$\left(D\frac{\partial C}{\partial \xi}\right)^{+} \approx D(C^{+} - C\ )/\Delta x \tag{A.3}$$

$$\left(D\frac{\partial C}{\partial \xi}\right)^{-} \approx D(C\ - C^{-})/\Delta x\,. \tag{A.4}$$

Substituting equations A.3 and A.4 in equation A.2 results in

$$\frac{\partial}{\partial \xi}(D\frac{\partial C}{\partial \xi}) \approx \frac{1}{\Delta x}\Big(\ \frac{D}{\Delta x}(C^{+} - C) - \frac{D}{\Delta x}(C - C^{-})\ \Big). \tag{A.5}$$

Then using equation A.5 in equation A.1, we get a new approximating formula for $\int_{t}^{t+\Delta t} \frac{\partial}{\partial \xi}(D\frac{\partial C}{\partial \xi})dt$ as,

$$\int_{t}^{t+\Delta t} \frac{\partial}{\partial \xi}(D\frac{\partial C}{\partial \xi})dt \approx \frac{\Delta t}{\Delta x}\Big(\ \frac{D}{\Delta x}(C^{+} - C) - \frac{D}{\Delta x}(C - C^{-})\ \Big). \tag{A.6}$$

Equation A.6 can be changed further by introducing mean flow velocity $|u|$ and mean cross section area S of water parcel as

$$\int_{t}^{t+\Delta t} \frac{\partial}{\partial \xi}(D\frac{\partial C}{\partial \xi})dt \approx \frac{|u|*S*\Delta t}{\Delta x * S}\Big(\ \frac{D}{\Delta x*|u|}(C^{+} - C) - \frac{D}{\Delta x*|u|}(C - C^{-})\ \Big). \tag{A.7}$$

Since

- channel flow, $Q = |u| * S$,
- volume of the water parcel under study, $V_p = \Delta x * S$.

Then the final form of equation A.1 is

$$\int_t^{t+\Delta t} \frac{\partial}{\partial \xi}(D\frac{\partial C}{\partial \xi})dt \approx \frac{Q\Delta t}{V_p}\left(\frac{D}{\Delta x * |u|}(C^+ - C) - \frac{D}{\Delta x * |u|}(C - C^-) \right). \tag{A.8}$$

As stated previously, define a new dispersion factor D_f as

$$D_f = \frac{D}{|u|\Delta x} \tag{2.4}$$

Equation A.8 can be simplified as

$$\int_t^{t+\Delta t} \frac{\partial}{\partial \xi}(D\frac{\partial C}{\partial \xi})dt \approx \frac{Q\Delta t}{V_p}\left(D_f(C^+ - C) - D_f(C - C^-) \right) \tag{A.9}$$

Equation A.9 is a reasonable approximation for steady flow. If we extend it to unsteady flow, the variation of dispersion factor D_f needs to be considered because values of D_f depend on flow. Assuming D_f^+, D_f^- as the dispersion factors at the upstream and downstream borders of the parcel under study, equation A.9 becomes equation 2.3:

$$\int_t^{t+\Delta t} \frac{\partial}{\partial \xi}(D\frac{\partial C}{\partial \xi})dt \approx \frac{|Q|\Delta t}{V_p}[D_f^+(C^+ - C) - D_f^-(C - C^-)]$$

Appendix 2B Numerical Experiment on Varied Values of Dispersion Factor

The objective of the numerical experiment in this appendix is to test the conservation of constituent mass when the value of the Qual dispersion factor is set higher than 1. The result of the experiment is a comparison of continuity error of simulated mass on a specific branch for different values of the dispersion factor.

2B.1 Model Setting

This small model consists of 6 branches with equal length of 15,000 feet and the same square cross-section everywhere (Figure 2B-1).

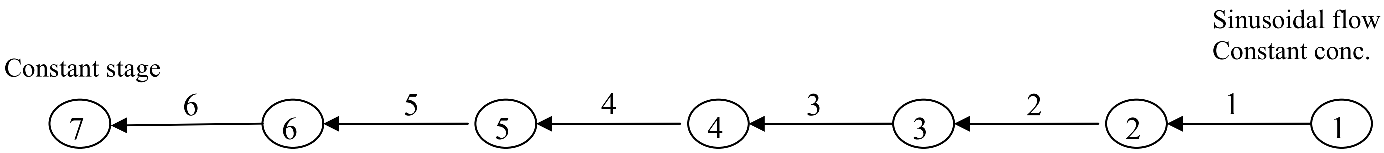

Figure 2B-1 Model grid

As shown in the model grid, a sinusoidal flow with constant concentration was placed on the upstream boundary, and a constant stage on the downstream boundary. It is assumed the simulated constituent is conservative, and an experiment was carried out for dispersion factors of 0.3, 3, and 10. To check mass conservation, the error of continuity is calculated by formula

$$error = \frac{M_t + M_{inout} - M_0}{M_0},$$

where M_t is the mass left in the branch at the end of a time step, M_0 is the mass in the branch at the beginning of a time step, and M_{inout} is the simulated mass in or out of the branch during a time step.

2B.2 Experiment Result

Experiment shows the mass continuity error for different dispersion factors is zero during the simulation period; that is, mass is conserved in the experiment.

Appendix 2C Underestimating Mass Transport by Qual Implementation

This appendix addresses the issue of underestimating mass transport during a time step.

Because of the limitation of the implementation, Qual cannot track the constituent mass transported from locations that are beyond the immediate upstream branch of the branch under study. Figure 2C-1 demonstrates an instance of such a situation.

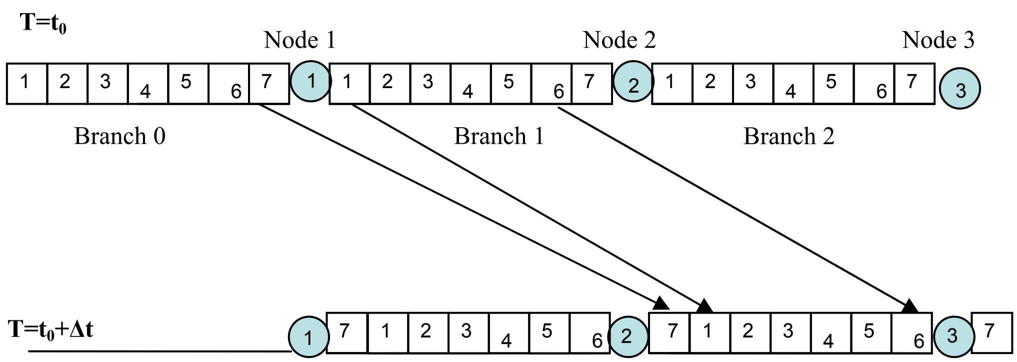

Figure 2C-1 Qual mass transport implementation

In the scenario shown above, we chose branch 2 as a study object. After a time step, the original water within branch 2 is totally displaced by parcels from branch 1 (1, 2, 3, 4, 5, 6) and branch 0 (7). Qual can handle the mass transported from branch 1 correctly; however, it does not account for mass transported from branch 0. Thus, the concentration predicted by Qual for the end of time step is lower than the correct value.

This scenario happens when flow is so high that all the old water parcels within a branch are flushed in less than one time step. For instance, for a rectangular branch with a length of 1,000 feet and width of 10 feet, steady water depth of 2 feet, and the time step of Qual interval at 15 minutes, the limiting flow can be estimated as

$$Q = (1000 * 2 * 10) / (15 * 60) = 22 cfs$$

To avoid such an error in Qual, the user may need to choose a short enough time step based on estimates of flows in the channels under study.

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Chapter 3: Impacts of Sea Level Rise and Amplitude Change on Delta Operations

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3 Impacts of Sea Level Rise and Amplitude Change on Delta Operations

3.1 Introduction

In this chapter, we quantify impacts on Sacramento-San Joaquin Delta operations and salinity increases at some key locations of the Delta. These impacts are caused by sea level rise (1 foot and 2 feet) and change in tidal amplitude (4 inches). With Delta Simulation Model II (DSM2), we calculated the salinity at key locations in the Delta and trained Artificial Neural Networks (ANNs) for each of the 5 sea-level-rise scenarios. The generated ANNs are flow-salinity relationships that calculate electrical conductivity (EC) at a given location using Delta boundary flows. With CalSim II (Central Valley Project [CVP] and State Water Project [SWP] operation model), we determined the extra cost of water to mitigate the sea level rise and tidal amplitude change. We assumed current operation rules (State Water Resources Control Board Decision 1641) were unchanged.

3.2 Background

3.2.1 Sea Level Rise Estimates

Intergovernmental Panel on Climate Change

The Third Assessment report of the Intergovernmental Panel on Climate Change (IPCC 2001) projected a global mean sea rise by 0.3 feet to 2.9 feet between 1990 and 2100 for the full range of greenhouse gas emissions described in IPCC's Special Report on Emission Scenarios (IPCC SRES).

The IPCC Fourth Assessment Report of 2007 (IPCC 2007) projected a sea level increase from 0.6 feet to 1.93 feet for this century (2000 to 2100) depending on selected emission scenarios (Table 3-1). Compared to the third assessment, the fourth assessment reduces the estimated projection of sea level rise by nearly 1 foot.

Table 3-1 Projected sea level rises

	Temperature change (°C at 2090-2099 relative to 1980-1999)		Sea-level rise (feet at 2090-2099 relative to 1980-1999)
Greenhouse gas scenarios	Best estimate	*Likely* range	Model-based range excluding future rapid dynamical changes in ice flow
Constant year 2000 concentrations	0.6	0.3 – 0.9	NA
B1 scenario	1.8	1.1 – 2.9	0.59 – 1.25
A1T scenario	2.4	1.4 – 3.8	0.66 – 1.48
B2 scenario	2.4	1.4 – 3.8	0.66 – 1.41
A1B scenario	2.8	1.7 – 4.4	0.69 – 1.57
A2 scenario	3.4	2.0 – 5.4	0.75 – 1.67
A1FI scenario	4.0	2.4 – 6.4	0..85 – 1.94

3.2.2 CALFED Independent Science Board

Dr. Jeffrey Mount, chair of the CALFED Independent Science Board, stated (Mount 2007):

> "During the past year, there have been major advances in the science of sea level rise. Paradoxically, these advances have increased the uncertainty of projections in sea level rise, at least temporarily. These advances have also led to strong criticism of the approach that the IPCC used in establishing its projections. One criticism is that the models used to project sea level rise tend to under-predict historical sea level rises, most notably failing to capture recent increases. Indeed, models that use empirical historical relationships between global temperatures and sea level rise perform better than the IPCC 2007 models. When applied to the range of emission scenarios used by IPCC 2007, empirical models project a mid-range rise this century of 70-100 cm (28-39 in.) with a full range of variability of 50-140 cm (20-55 in.), substantially higher than IPCC 2007 projections."

3.2.3 Tidal Amplitude Change Estimates

In "Trends in United States Tidal Datum Statistics and Tide Range," Flick *et al.* (2003) reported significant changes in the diurnal tide range (mean higher high water [MHHW] – mean lower low water [MLLW]) or mean tide range (mean high water [MHW] – mean low water [MLW]). In San Francisco, the diurnal tide range increased by 2.5 inches from 1990 to 1998. In the absence of any other scientific projections for future changes in the ocean amplitude for this century, we assumed a 4-inch (approximately 10%) increase in the tidal amplitude for the year 2100.

3.2.4 Martinez Salinity Change Estimates

DSM2 uses Martinez as its seaward boundary. For a planning tide, Martinez EC is calculated using a complex relationship between several EC stations and net Delta outflow. However, with changes in sea level, this relationship cannot be used to compute Martinez EC. Different sea-level-rise scenarios and their impacts on the western Delta were studied by Dr. Edward Gross and documented in Appendix H3 of the Delta Risk Management Strategy (DRMS) Phase 1 report for the California Department of Water Resources (URS 2007). Dr. Gross considered 4 levels of sea level rise: 8 inches, 20 inches, 36 inches, and 56 inches. In addition, he studied effects caused by an 11% tidal amplitude increase. Assuming climate change does not affect ocean salinity, Gross used the multi-dimensional TRIM model to calculate salinity increases in the western Delta. The DRMS report contains figures that show increases in Martinez EC projected by different studies. By linearly interpolating these figures, we calculated approximate Martinez EC increases (Table 3-2).

Table 3-2 Martinez EC increases by alternative

Alternatives	Martinez EC (% increase from baseline)
Amplitude increase 4 inches	2%
1 ft mean sea level rise	3%
1 ft MSL + 4-inch amp change	5%
2 ft mean sea level rise	7%
2 ft MSL + 4-inch amp change	9%

MSL = mean sea level

Because these values are approximate, we conducted a sensitivity study to determine the effects that a Martinez EC increase has on export water quality. Table 3-3 shows the increase in EC at Banks and Jones export locations due to an increase in EC at Martinez. For the 6-month period February through July, the impact of a Martinez EC increase is negligible. For the period August through January, the effect of a Martinez EC increase is less than 4%.

Table 3-3 Export EC increases from Martinez EC increase

Martinez	Banks Pumping Plant		Jones Pumping Plant	
(EC increase)	(Aug-Jan)	(Feb-July)	(Aug-Jan)	(Feb-July)
2%	0.75%	0.19%	0.64%	0.16%
5%	1.88%	0.47%	1.60%	0.41%
7%	2.63%	0.66%	2.23%	0.57%
9%	3.38%	0.85%	2.87%	0.73%

3.3 Numerical Models

3.3.1 Delta Simulation Model II (DSM2)

DSM2 assumes no bank overtopping. Hence, it is assumed that Delta levees are high enough to prevent water overflowing the banks at peak sea level rise (2 foot-sea level rise and 4-inch tidal amplitude increase).

DSM2 assumes no tidal reflections at the upstream boundaries. For the purpose of this study, both Sacramento River and San Joaquin River were extended upstream by about 10 miles to gain an elevation increase of 3 feet.

3.3.2 Artificial Neural Networks

The standard ANNs use 6 inputs to predict salinity at 6 locations in the Delta where salinity standards have to be met. The 6 locations are Emmaton, Jersey Point, Old River at Rock Slough, Collinsville, Chipps Island, and Antioch (Figure 3-1). The ANNs were expanded to

3 more locations, namely CVP intake (Jones pumping plant), Clifton Court Forebay intake (Banks pumping plant), and Los Vaqueros intake at Old River. This enables CalSim II to determine salinity at export locations without using DSM2, which is very time-consuming.

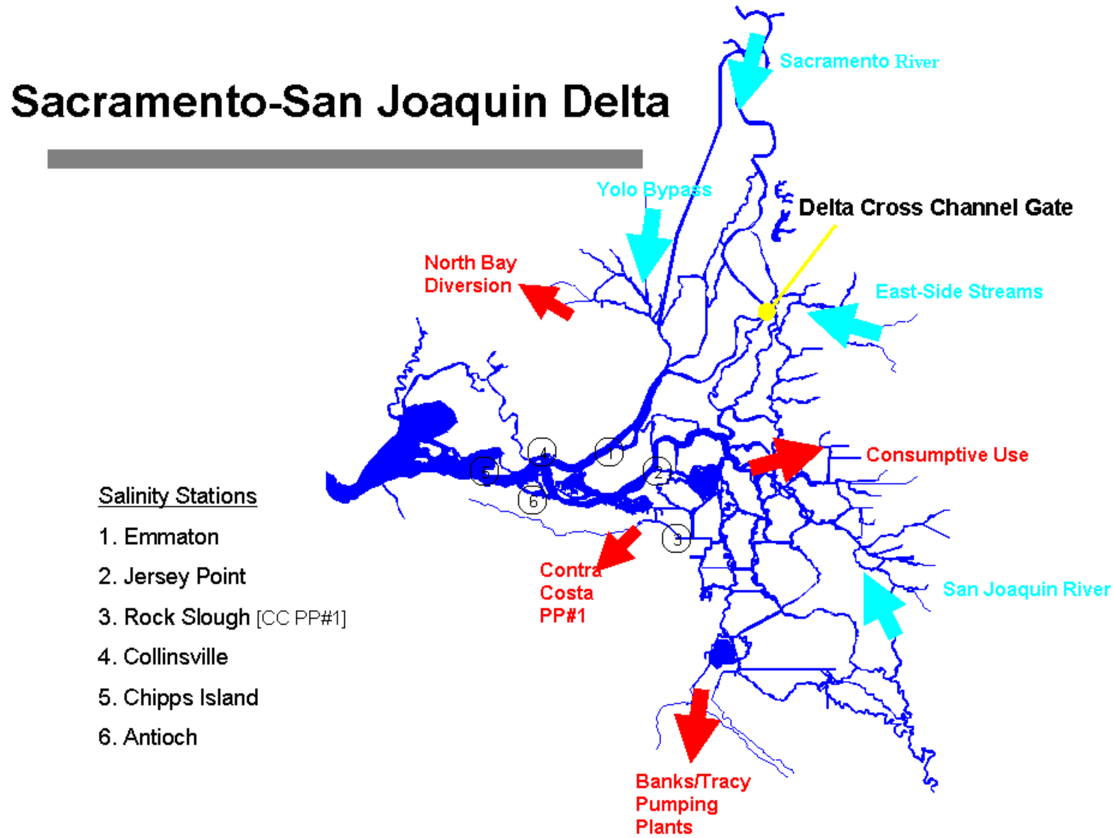

Figure 3-1 Sacramento-San Joaquin Delta

At present, CalSim II uses Kimmerer-Monismith (KM) equations to calculate X2 (salinity of 2 ppt) locations in the Delta for a given Delta outflow. The empirical formula developed by KM used observed data. This equation ceases to be valid when the downstream boundary stage is different from historical conditions. The DSM2 model was used to develop new ANNs for X2 for the base case and different sea-level-rise scenarios. These were implemented in CalSim II.

3.3.3 CalSim II

For the purpose of this study, SWP and CVP were operated according to the State Water Resources Control Board Decision 1641 (D1641). D1641 implements flow and salinity objectives for the San Francisco Bay-Delta estuary. In a standard CalSim II study under D1641, salinity standards are only enforced at Emmaton, Jersey point, Old River at Rock Slough, and Collinsville. Studies show that in almost all cases when salinity standards are met at these 4 stations, salinity standards are also met at other locations described in D1641.

For some scenarios of sea level rise, CalSim II terminated simulation when reservoirs dried up in extreme dry years. To circumvent this, we (artificially) added some water for these dry years.

3.4 Results

3.4.1 Salinity at Key Locations in the Delta

Without changing any operations (inflows to Delta, Exports, and Delta Cross Channel operation), we conducted DSM2 studies for 5 different sea-level-rise scenarios. Table 3-4 compares calculated EC changes at SWP (Banks Pumping Plant) and CVP (Jones Pumping Plant) export locations in the Delta for each of the 5 scenarios. The results show the percent increase in EC from the baseline. Monthly average EC increase for some key locations in the Delta are listed in Appendix 3B.

Table 3-4 Export EC increases by alternative

	Banks Pumping Plant		Jones Pumping Plant	
Alternatives	(Aug-Jan)	(Feb-July)	(Aug-Jan)	(Feb-July)
Amplitude increase 4 inches	14%	4%	12%	4%
1 ft mean sea level rise	10%	3%	9%	3%
1 ft MSL + 4-inch amp change	25%	9%	21%	8%
2 ft mean sea level rise	21%	7%	18%	7%
2 ft MSL + 4-inch amp change	38%	14%	33%	12%

3.4.2 Operation Cost

CalSim II model was run for a 73-year period. The following tables (3-5 through 3-9) show the reduction in the ability to deliver water in the 5 sea-level-rise scenarios for 3 significantly important periods: long-term average (1922–1993), long-term drought periods (1928–1934, and 1986–1992), and the most severe drought (1976–1977). For some sea-level-rise scenarios, the system dried out and additional (artificial) water had to be introduced just to proceed with CalSim II simulations. These are listed as notes under tables 3-7, 3-8, and 3-9.

Table 3-5 Export delivery changes for 4-inch amplitude increase

	SWP Delivery (taf)			CVP Delivery (taf)		
Periods	Base	change	% change	Base	change	%change
1928-1934	1709	-325	-19.0%	1506	3	0.2%
1976-1977	1386	29	2.1%	1453	-39	-2.7%
1986-1992	1844	-166	-9.0%	1774	-10	-0.6%
1922-1993	3205	-115	-3.6%	2536	-28	-1.1%

taf = thousand acre-feet

Table 3-6 Export delivery changes for 1-foot sea level rise

	SWP Delivery			CVP Delivery		
Periods	Base	change	%change	Base	change	%change
1928-1934	1709	-111	-6.5%	1506	-42	-2.8%
1976-1977	1386	-8	-0.6%	1453	-61	-4.2%
1986-1992	1844	-142	-7.7%	1774	-44	-2.5%
1922-1993	3205	-64	-2.0%	2536	-61	-2.4%

Table 3-7 Export delivery changes for 1-foot sea level rise + 4-inch amplitude increase

	SWP Delivery			CVP Delivery		
Periods	Base	change	%change	Base	change	%change
1928-1934	1709	-301	-17.6%	1506	-16	-1.1%
1976-1977	1386	-230	-16.6%	1453	-10	-0.7%
1986-1992	1844	-207	-11.2%	1774	-72	-4.1%
1922-1993	3205	-152	-4.8%	2536	-52	-2.0%

Note: Amount of water added to prevent termination of model simulation.
Water year (WY) 1934 = 43 taf
WY 1935 = 30 taf
WY 1978 = 105 taf

Table 3-8 Export delivery changes for 2-foot sea level rise

	SWP Delivery			CVP Delivery		
Periods	Base	change	%change	Base	change	%change
1928-1934	1709	-497	-29.1%	1506	-83	-5.5%
1976-1977	1386	-254	-18.3%	1453	-58	-4.0%
1986-1992	1844	-276	-15.0%	1774	-110	-6.2%
1922-1993	3205	-214	-6.7%	2536	-77	-3.1%

Note: Amount of water added to prevent termination of model simulation.
WY 1978 = 207 taf
WY 1992 = 11 taf
WY 1993 = 29 taf

Table 3-9 Export delivery changes for 2-foot sea level rise + 4-inch amplitude increase

	SWP Delivery			CVP Delivery		
Periods	Base	change	%change	Base	change	%change
1928-1934	1709	-607	-35.5%	1506	-99	-6.6%
1976-1977	1386	-410	-29.6%	1453	-94	-6.5%
1986-1992	1844	-350	-19.0%	1774	-183	-10.3%
1922-1993	3205	-360	-11.2%	2536	-115	-4.5%

Note: Amount of water added to prevent termination of model simulation.
WY 1931 = 44 taf
WY 1932 = 33 taf
WY 1934 = 43 taf
WY 1935 = 35 taf
WY 1977 = 3 taf
WY 1978 = 263 taf
WY 1991 = 56 taf
WY 1992 = 187 taf
WY 1993 = 164 taf

3.5 Conclusions

- Change in tidal amplitude impacts project operations more severely than mean sea level rise.
- Change in Martinez EC does not significantly impact the water quality at the interior Delta or at the SWP and CVP export pumps.
- Ocean salt dominates the salinity in the interior Delta during the 6-month period August through January. Impacts of sea level rise are greater during this period.
- For one-foot sea level rise with 4-inch change in tidal amplitude, CVP and SWP export water quality degrades more than 20% for the same volume of exports during the months of August through January.
- For one-foot sea level rise with 4-inch change in tidal amplitude, additional water must be introduced in spite of SWP deliveries being cut by 5% over a long period and by more than 15% during drought periods.

3.6 References

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Appendix 3A Impacts of Martinez Salinity Changes at Key Delta Locations

We conducted DSM2 fingerprinting studies to determine the EC contribution from Martinez at a given location. The following tables show monthly changes in EC at Martinez and their effect on EC at other locations.

Emmaton

Martinez EC % increase	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
2%	1.66%	1.50%	1.37%	1.05%	0.68%	0.43%	0.48%	0.84%	1.18%	1.44%	1.67%	1.69%
5%	4.14%	3.75%	3.41%	2.61%	1.70%	1.08%	1.21%	2.11%	2.96%	3.60%	4.18%	4.22%
7%	5.80%	5.25%	4.78%	3.66%	2.38%	1.51%	1.69%	2.96%	4.14%	5.04%	5.85%	5.91%
9%	7.45%	6.76%	6.14%	4.70%	3.06%	1.94%	2.17%	3.80%	5.32%	6.48%	7.52%	7.59%

Jersey Point

Martinez EC % increase	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
2%	1.61%	1.59%	1.45%	1.30%	0.84%	0.54%	0.37%	0.67%	0.96%	1.24%	1.60%	1.68%
5%	4.02%	3.97%	3.61%	3.24%	2.09%	1.36%	0.92%	1.68%	2.40%	3.09%	4.01%	4.21%
7%	5.62%	5.55%	5.06%	4.54%	2.93%	1.90%	1.29%	2.36%	3.36%	4.33%	5.61%	5.90%
9%	7.23%	7.14%	6.50%	5.84%	3.77%	2.44%	1.66%	3.03%	4.32%	5.56%	7.21%	7.58%

Old River at Rock Slough

Martinez EC % increase	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
2%	1.29%	1.28%	1.23%	1.06%	0.72%	0.38%	0.17%	0.20%	0.41%	0.65%	1.00%	1.32%
5%	3.22%	3.21%	3.08%	2.65%	1.80%	0.95%	0.43%	0.50%	1.03%	1.63%	2.50%	3.31%
7%	4.51%	4.49%	4.31%	3.71%	2.51%	1.33%	0.61%	0.69%	1.44%	2.28%	3.50%	4.64%
9%	5.80%	5.78%	5.55%	4.77%	3.23%	1.71%	0.78%	0.89%	1.85%	2.93%	4.50%	5.96%

SWP (Banks Pumping Plant)

Martinez EC % increase	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
2%	0.82%	0.79%	0.83%	0.65%	0.37%	0.18%	0.06%	0.04%	0.16%	0.34%	0.55%	0.86%
5%	2.06%	1.97%	2.07%	1.62%	0.93%	0.44%	0.15%	0.09%	0.39%	0.85%	1.38%	2.16%
7%	2.89%	2.76%	2.90%	2.26%	1.31%	0.62%	0.21%	0.13%	0.54%	1.18%	1.93%	3.02%
9%	3.71%	3.55%	3.73%	2.91%	1.68%	0.79%	0.26%	0.17%	0.70%	1.52%	2.48%	3.89%

CVP (Jones Pumping Plant)

Martinez EC % increase	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
2%	0.72%	0.68%	0.70%	0.52%	0.32%	0.14%	0.04%	0.02%	0.14%	0.31%	0.47%	0.73%
5%	1.81%	1.70%	1.75%	1.30%	0.81%	0.35%	0.10%	0.06%	0.34%	0.78%	1.19%	1.83%
7%	2.53%	2.38%	2.46%	1.82%	1.13%	0.49%	0.13%	0.08%	0.48%	1.09%	1.66%	2.56%
9%	3.25%	3.06%	3.16%	2.34%	1.45%	0.63%	0.17%	0.11%	0.61%	1.40%	2.13%	3.30%

Appendix 3B Monthly Average EC Increase at Different Locations for Different Sea Level Rise Scenarios

Emmaton

Alternatives	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Amplitude increase 4"	25%	24%	26%	25%	22%	17%	20%	24%	26%	28%	27%	25%
1 ft mean sea level rise	17%	18%	21%	19%	18%	12%	12%	12%	13%	16%	15%	16%
1 ft MSL + 4" Amp Change	42%	41%	47%	46%	43%	32%	36%	41%	43%	46%	43%	41%
2 ft mean sea level rise	33%	35%	41%	39%	37%	26%	26%	27%	29%	33%	31%	31%
2 ft MSL + 4" Amp Change	60%	60%	71%	69%	67%	50%	54%	59%	63%	67%	62%	59%

Jersey Point

Alternatives	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Amplitude increase 4"	24%	23%	21%	20%	17%	13%	14%	23%	27%	26%	26%	22%
1 ft mean sea level rise	19%	19%	18%	18%	17%	13%	10%	13%	15%	17%	18%	17%
1 ft MSL + 4" Amp Change	43%	43%	39%	38%	36%	29%	29%	41%	47%	47%	47%	39%
2 ft mean sea level rise	39%	39%	37%	37%	36%	30%	24%	31%	35%	37%	38%	34%
2 ft MSL + 4" Amp Change	66%	65%	60%	60%	57%	49%	48%	64%	73%	71%	70%	58%

Old River at Rock Slough

Alternatives	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Amplitude increase 4"	24%	25%	22%	17%	14%	7%	5%	7%	13%	17%	23%	24%
1 ft mean sea level rise	19%	20%	18%	16%	13%	8%	5%	5%	7%	10%	14%	17%
1 ft MSL + 4" Amp Change	45%	47%	42%	34%	28%	16%	10%	14%	24%	31%	40%	44%
2 ft mean sea level rise	40%	42%	39%	33%	27%	18%	10%	11%	16%	23%	31%	36%
2 ft MSL + 4" Amp Change	70%	73%	65%	54%	45%	28%	18%	22%	36%	48%	62%	67%

SWP (Banks Pumping Plant)

Alternatives	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Amplitude increase 4"	15%	15%	15%	10%	7%	3%	1%	1%	5%	9%	13%	16%
1 ft mean sea level rise	10%	11%	12%	9%	7%	4%	1%	1%	2%	5%	8%	10%
1 ft MSL + 4" Amp Change	27%	27%	27%	19%	14%	8%	3%	2%	9%	15%	23%	28%
2 ft mean sea level rise	22%	23%	24%	19%	14%	9%	3%	2%	6%	11%	17%	21%
2 ft MSL + 4" Amp Change	40%	41%	41%	30%	23%	13%	6%	4%	14%	24%	35%	41%

CVP (Jones Pumping Plant)

Alternatives	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Amplitude increase 4"	13%	13%	12%	8%	6%	2%	1%	1%	4%	8%	11%	14%
1 ft mean sea level rise	9%	10%	10%	7%	6%	3%	2%	1%	2%	5%	7%	9%
1 ft MSL + 4" Amp Change	24%	24%	23%	15%	12%	6%	3%	2%	8%	15%	20%	24%
2 ft mean sea level rise	19%	20%	20%	15%	12%	7%	4%	3%	6%	11%	15%	18%
2 ft MSL + 4" Amp Change	36%	36%	35%	24%	19%	11%	5%	4%	12%	23%	30%	36%